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Static planning of the expansion of electrical energy transmission systems using particle swarm optimization

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ABSTRACT

Static planning of the expansion of electrical energy transmission systems consists of determining, among a pre-defined set of candidate expansion circuits, which ones must be built to minimize the operational costs (deficit) and investment in the electrical system, supplying the predicted demand for a planning horizon. Considering this problem, the proposed methodology uses a Constructive Heuristic Algorithm (CHA) to identify the most relevant route from a set of candidate expansion routes to reduce the search space and, consequently, increase the efficiency of the bio-inspired particle swarm search process. Therefore, the proposed methodology is divided into two stages: (i) obtaining the reduced set of candidate expansion routes using the CHA to decrease the search space without losing relevant expansion paths; (ii) using particle swarm optimization and heuristic information from the first stage to find the minimum expansion cost of the transmission system. In both stages, the transmission system is represented by the linearized load flow model, where the expansion decisions are incorporated into the problem using the original equations of the DC model. The proposed methodology was applied to the Garver system and to two real equivalent systems for the South and Southeast of Brazil, where the efficiency of the proposed system can be verified.

1. Introduction

The rapid growth of electrical service demand, the large territorial dimensions of Brazil and the large distances between the hydroelectric plants and consuming centers make the long distance transport of large amounts of energy necessary, requiring an adequate electrical energy transmission system. The characteristics mentioned contribute to the electrical system planning problem that, in general, becomes a complex task, with the objective of guaranteeing service to consumers at the lowest possible cost. Thus, the agents must decide when (dynamic vision) and where (static vision) to invest the available financial resources in an optimal manner to guarantee reliable and adequate functioning of the electrical power system. In general, these decisions are associated with the selection of the most economical generating units and the best routes for electrical energy transmission and distribution. For this purpose, strategies must be developed to guarantee that the decisions adopted during the planning process are optimal or, economically, very close to optimal. According to the mentioned premises, static planning of the expansion of the electrical energy transmission system is a complex, large-scale optimization problem.

The static planning problem for expanding the transmission system consists of determining, from one pre-defined set of candidate expansion circuits, the circuits that must be built to minimize operational costs (deficit) and investment in the transmission system, meeting the predicted demand for a planning horizon. This optimization problem is a difficult one with some peculiarities, such as (i) a non-convex solution region with various feasible solutions, which leads to a large portion of the algorithms converging in the direction of a local optimal solution; (ii) the combinatorial nature of the planning process, which normally leads to the combinatorial explosion phenomenon related to investment alternatives, resulting in elevated computational effort; (iii) the existence of unconnected (isolated) electrical systems. These peculiarities illustrate the primary difficulties in the elaboration of rapid, efficient and robust algorithms for resolving the static problem of electrical energy transmission systems expansion.

Through a literature analysis, three large groups of algorithms can be distinguished to solve the static planning problem for the expansion of electrical energy transmission systems: (i) Constructive Heuristic Algorithms are robust and require little computational effort, but they rarely find the global optimum solution, particularly in real and/or large scale systems [1–3]. (ii) Classical

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Nomenclature

nr	number of fictitious generators
nc	number of candidate circuits
c_m	cost of the energy deficit (US$/MW year)
c_k	construction cost for candidate circuit k (US$/year)
g_i	generation on bus i (MW)
$\bar{g}_i$	MAXIMUM generation limit on bus i (MW)
r_i	fictitious generation on bus i (MW)
$\bar{r}_i$	maximum limit of fictitious generation on bus i (MW)
Ωi	set of buses connected to bus i
EP_k	expansion parameter for candidate circuit k, integer variable 0/1
f_{ij}	active power flow in circuit $i-j$ (MW)
$\bar{f}_{ij}$	limit of active power flow in circuit $i-j$ (MW)
γ_{ij}	susceptance of circuits $i-j$
d_i	demand on bus i (MW)
φ_{ij}	angular difference of the fictitious circuit between the buses $i-j$
θ_{ij}	angular difference between the buses $i-j$
$\gamma_{ij_{FIC}}$	susceptance of the fictitious circuit $i-j$
V_k	particle velocity in iteration k
V_{k-1}	particle velocity in the previous iteration
w	inertial weight
c_1, c_2	positive constants that correspond to the cognitive and social parameters of the particles
$rand$	random number generator on the interval [0, 1]
$pbest_{k-1}$	best position of particle k until the previous iteration
$gbest_{k-1}$	best swarm position until the previous iteration
$X_{k,i}$	position of particle k in iteration i
$X_{k-1,i}$	position of particle k in the previous iteration
w	inertial weight
$w_{\max}$	maximum inertial weight
$w_{\min}$	minimum inertial weight
$iter$	current iteration
$iter_{\max}$	maximum number of iterations

Optimization Algorithms use mathematical decomposition techniques and generally find global optimum solutions for small and medium-sized systems. For large systems, these algorithms can show problems related to computational effort and, in some cases, convergence problems [4–6]. (iii) Meta-heuristics find optimal or suboptimal solutions, even in large-scale systems, but they generally require high computational effort. Despite the processing time, however, the use of meta-heuristics [7–9] has grown in recent years, as will be reported below.

Cortes-Carmona et al. [10] use the Simulated Annealing technique to solve the planning problem for the expansion of electrical energy transmission systems. A hybrid algorithm is used to perform a local search that refines the solution found at each temperature level, permitting a reduction in processing time. The methodology showed good results with low processing time.

Tabu Search is another technique used to solve the planning problem of transmission systems expansion. This meta-heuristic was combined with the GRASP method (Greedy Randomized Adaptive Search Procedure) to perform the search for feasible initial solutions [11]. This hybrid method was shown to be interesting, as it makes use of previously acquired knowledge during its exploration of the solution space to escape local minima during the search trajectory of the final solution.

Another hybrid methodology was used in [12], which applied Parallel Tabu Search and an optimization algorithm known as Ordinal Optimization. The latter was employed to minimize the number of candidate expansion circuits, reducing the effects of combinatorial explosion and notably accelerating the computational time of the search process.

A Genetic Algorithm was used in [13], where modifications were proposed in the original algorithm to obtain an improvement in the generation phase of the descendants and increase the population diversity. The local improvement of a solution (individual) was proposed through the use of a constructive heuristic, which added the candidate expansion circuits in decreasing order of cost, so that solutions that would produce an elevated expansion cost could be eliminated.

Verma et al. [14] proposed the use of a particle swarm, with adaptations, for the expansion of electrical energy transmission systems. These adaptations were made with the objective of increasing the search capacity of the swarm. The results were considered satisfactory, and the particle swarm was shown to be a powerful tool for the problem under analysis.

The Shuffled Frog Leaping (SFL) meta-heuristic was used in [15]. Through an initial random population, the technique showed optimal convergence and interesting results when compared to other meta-heuristics, such as particle swarm and genetic algorithm.

In the bibliographic review, it can be found that numerous characteristics, properties and results from constructive heuristics are useful in the development of more complex algorithms. Thus, this study proposes the use of a Constructive Heuristic Algorithm to find a reduced set of relevant expansion routes. With the reduced set defined, this set is provided to the bio-inspired particle swarm search process (meta-heuristic), which determines the final planning for the expansion of the electrical energy transmission system.

2. Formulation of the problem

For the problem of expansion planning for an electrical energy transmission system, the DC load flow model is traditionally used. This model is based on the coupling between active power and the voltage angle and makes it possible to determine the distribution of the active power flows in the transmission network with low computational effort and acceptable precision in a simple manner. Thus, given that E is the set of circuits existing in the base topology of an electrical power system, C is the set of candidate expansion circuits, and F is the set of fictitious circuits, the optimization problem can be formulated as follows:

$$Min \sum_{m=1}^{nr} c_m . r_m + \sum_{k=1}^{nc} c_k \cdot EP_k \tag{1}$$

subject to

$$g_i + r_i + \sum_{j \in \Omega i} f_{ij} = d_i \tag{2}$$

$$|f_{ij}| \leqslant \bar{f}_{ij} \quad \forall (i,j) \in E, C \tag{3}$$

$$0 \leqslant g \leqslant \bar{g} \tag{4}$$

$$0 \leqslant r \leqslant \bar{r} \tag{5}$$